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Studies of Ignition Behavior of Biomass Particles in a Down-Fire Reactor for Improving Co-firing Performance

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ABSTRACT: To realize large-percentage biomass co-firing with coal in existing coal-fired boilers, the combustion behavior of biomass is expected to be similar or comparable to that of coal. When co-firing with coal, biomass is not necessarily to be ground as fine as the dedicated coal particles, because of its higher reactivity. With the objective of achieving promising performance of co-firing with dedicated coal particles, the determination of suitable biomass particle size becomes important. The paper investigates experimentally the ignition behavior of three biomass materials in a down-fire reactor associated with thermogravimetric analysis (TGA). TGA results showed that the devolatilization process is accelerated by the presence of oxygen, but failed to identify the impacts of particle size on the ignition behavior of biomass. However, the ignition testing results based on the down-fire reactor clearly show that the ignition delay time of a large biomass particle is longer than that of a smaller one. In addition, when injected into the furnace, the softwood particles require a longer residence time to be ignited than the straw particles of the same size, which agrees well with their reactivity analysis in TGA. Moreover, the ignition test results suggested that the ignition mechanism of biomass could be alternated from homogeneous ignition to heterogeneous ignition when the furnace temperature is increasing; at sufficiently high furnace temperatures, the ignition predictably occurs at the particle surface without requiring the start of devolatilization. The results quantitatively demonstrate the effects of particle size on the ignition delay time of biomass, which, together with the transport phenomena and surrounding atmosphere, can contribute to control the biomass combustion profile and co-firing performance.

1. INTRODUCTION

Biomass can be used as a sustainable fuel across the energy spectrum for electricity, heat, and transport. Compared to other thermal utilizations, biomass co-firing has been identified as a near-term, low-cost, and transitional means to increase biomass power capacity and reduce carbon emission. It has been demonstrated that biomass can potentially substitute more than 50% of the coal in a co-firing configuration, but presently, the actual co-firing levels in most commercial applications are only 5%−10% on a thermal basis.[1] When co-firing biomass with coal in existing coal-fired boilers, the differences of fuel properties between biomass and coal complicate the processes of fuel mixture handling and combustion. Typically, the high moisture content inherent in biomass requires more energy for drying and milling, resulting in decreased overall energy efficiency and increased difficulties in fuel handing and processing; while high oxygen and volatile contents of biomass might cause the discrepancies in combustion process when co-combusted with coal. Those technical challenges become critical when increasing the biomass co-firing ratios, thus limiting the widespread utilizations of biomass in power generation sectors.

Ignition is considered as the process that initiates combustion and is recognized as a critical step, because of its impact on the lift-off distance, the flame profile and stability, and the formation of pollutants, with the consequent influence on the boiler operation, energy efficiency, and emissions. Accordingly, understanding of the ignition behavior of biomass is essential in optimization of the biomass combustion or co-firing process. It is known that the ignition of solid fuel is the result of a complex interaction among different mechanisms, including particle heating, devolatilization, heterogeneous oxidation, and gas-phase oxidation and transport phenomena.[2] With regard to the reported ignition mechanisms, coal ignites either homogeneously as ignition of volatile matter evolved into the surrounding gas phase by pyrolysis of the coal particle, or heterogeneously as oxygen directly attacks the surface of the particle.[3] However, according to most ignition studies of coal particles, factors that bring about a given mechanism are still in disagreement, since it is a challenge to identify it via experimental approaches. Based on the theoretical definition of ignition type proposed by Zhang and Wall,[2] a high volatiles content in coal normally leads to a homogeneous ignition.

Compared to coal, biomass contains high volatiles and is known having a lower ignition temperature. The ignition or explosion of biomass dust clouds is of interest in the field of fire safety, which gained intensive research interests and has raised concerns over its safe handling and utilization.[4,5] Grotkjær et al.[4] conducted pulse ignition and thermogravimetric studies to determine the ignition temperature of three biomass materials. The results showed that the ignition process is initiated by oxidation reactions on the biomass particle surface, and then the volatiles form a homogeneous diffusion flame away from the particle surface. Jones et al.[5] recently observed that ignition occurred on the very reactive char particle formed via pyrolysis

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while flaming combustion of volatiles was not observed, and thus concluded that biomass ignition was heterogeneous but the results are based on smoldering combustion. With respect to biomass and coal co-firing, Riaza et al.[6] experimentally observed that the ignition behavior of the coals is improved by adding biomass in either air or oxy-firing conditions, particularly noticeable in the ignition of the high rank coal. Similarly, Toptas et al.[7] found that a blend of torrefied biomass with lignite coal has a reduced ignition temperature than lignite itself, and this was explained as the modified reactivity was a consequence of torrefaction of biomass but no interaction of lignite−biomass was seen in the first stage of co-combustion.

The characterization of solid fuel ignition is complicated since the ignition temperature is not a fundamental parameter of the fuel, which is highly dependent on the particle size, heating rate of the particle, and the surrounding gas.[4] When a fine biomass particle enters a pulverized fuel flame, it is rapidly heated to a final temperature that is far above its ignition temperature. Therefore, in the real combustion process, the ignition delay time becomes a key parameter, which, together with transport phenomena, determines the lift-off distance of flame and, consequently, the flame profile. To achieve large-percentage biomass co-firing in existing coal-fired boilers, the ignition and the consequent combustion properties of biomass are expected to be similar or comparable to that of coal.

Particle size distribution is essentially controlled for efficiently processing coal particles in dedicated coal-fired boilers. When co-firing biomass in these coal-fired boilers, it is believed that biomass does not need to be ground as fine as dedicated coal particles, because the reactivity of biomass is higher than that of coal, and thus biomass particles could be burnt out quickly inside boilers, even at bigger sizes.[8] Moreover, fine biomass particles are not favored, with respect to energy savings and co-firing performance. Cutting down the biomass sizes requires intensive energy, because of the fiber structure and high moisture content of biomass. In addition, fine biomass particles can be ignited immediately, which is an unwanted process, since the majority of the heat of its combustion is released at an early stage. Consequently, the high-temperature flame will primarily occur near the burner ports, leading to an extremely uneven heat distribution inside the furnace and thus unstable parameters of steam. However, an overly large biomass particle size should also be avoided, because its ignition could be delayed, and thus a considerable amount of unburnt carbon might still remain in fly ash, losing the thermal conversion efficiency. Therefore, understanding the influence of biomass particle size on ignition delay time is essential to determine the preferable sizes of biomass particles. This allows one to achieve an expected co-firing flame profile without boiler retrofitting and also ensure complete combustion of biomass particles before exiting the furnace, as well as to reduce the energy consumption in milling systems.

However, the effects of particle size on biomass ignition delay time and consequent combustion process are still unclear, and this uncertainty limits the control of a preferable flame profile and consequent combustion process. The impacts of particle sizes on coal ignition have been previously studied experimentally on a coal dust stream[9] or numerically on a single particle.[10] Obviously, because of the significantly different fuel properties of coal and biomass, coal ignition behavior could not be referenced for the understanding of biomass ignition properties. Regarding the coal and biomass fuel mixture, Trabadela[11] tested particle size effects on the coal and biomass ignition, and their results showed that the ignitions of fine biomass particles behaved similar in either air or oxygen-enriched conditions, while larger particles of biomass did not ignite, even in an oxygen-enriched atmosphere; however, only two different sizes of biomass particles were analyzed, which are insufficient to demonstrate a reasonable trend. In this work, straw, softwood, and torrefied softwood have been initially analyzed in thermogravimetric analysis (TGA) to understand their thermal performances under varying conditions; the TGA results are then used as the supportive fundamentals for understanding the tested ignition behavior of the biomass in a down-fire reactor. In addition, the ignition delay time of three types of biomass at varying particles sizes and furnace temperatures are determined by detecting the luminance changes inside the reactor before and after biomass ignition, using the photosensitive elements that are present at the top of the reactor. Finally, the time scales of ignition and devolatilization of different stages have been compared and comprehensively discussed.

2. METHODOLOGIES

2.1. Down-Fire Reactor. The ignition behavior of biomass particles is investigated experimentally in a down-fire reactor located in Wroclaw University of Technology (depicted in Figure 1). The height of reactor is 1100 mm, with an inner

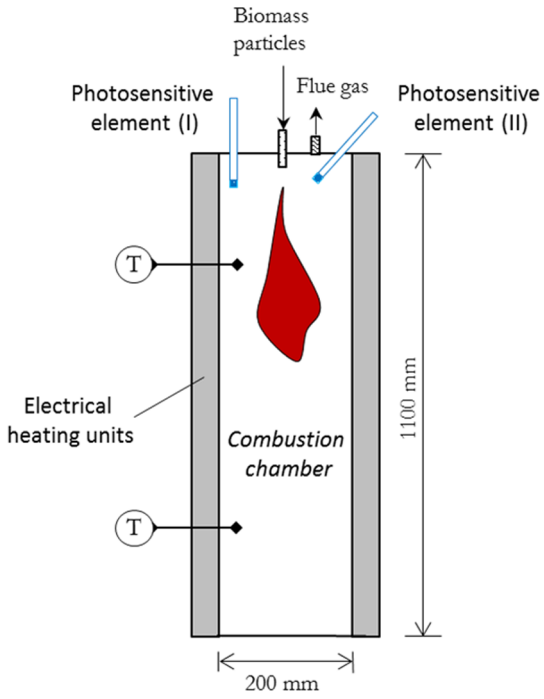

Figure 1. Schematic of the ignition test reactor.

diameter of 200 mm. Two-stage electrical heating units are equipped to ensure a maximum furnace temperature of 900 °C. The furnace temperatures are monitored by thermocouples at two height levels. Two photosensitive elements are equipped at the top of the reactor: one of them is installed vertically along the furnace (I), and the other one is installed at an angle of 45° (II), to ensure the interior of the reactor is fully monitored. The investigation of the ignition of the biomass particles is carried out in two steps. In the first step, the luminous emittance of the internal walls of the reactor is determined as the reference.

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Table 1. Fuel Properties

	Proximate Analysis (wt %)				Ultimate Analysis (wt %)					
	moisture ^{ar}	volatiles^{ar}	fixed carbon, FC^{ar}	ash^{ar}	C^{db}	H^{db}	O^{db}	N^{db}	S^{db}	lower heating value, LHV^{db} (MJ/kg)
straw	7.8	72.3	16.2	3.7	51.3	6.0	37.4	1.71	0.26	17.3
softwood	2.6	82.3	14.9	0.2	49.3	5.9	43.8	0.76	0.10	18.0
torrefied[a] softwood	1.4	81.3	17.1	0.2	53.9	4.4	40.6	0.76	0.10	19.8

[a]The torrefied biomass is produced by exposing the softwood particles in the oxygen-free furnace for 30 min at 250 °C.

Afterward, the sample is injected and the luminous emittance is measured and compared with the reference one. Once the ignition of biomass particles occurs, the heat released increases the temperature of the reactor walls and their luminous emittances, which is recorded by computer-controlled photosensitive elements. The ignition delay time is determined as the difference between the time of injection of the sample and the time at which ignition occurs.

Straw, softwood, and torrefied softwood are studied in this work to compare their ignition delay times under varying conditions; their fuel properties are listed in Table 1. To investigate the effects of particle size on the ignition, samples with different particle sizes of each type fuel are prepared and tested at variable temperatures, and the ignition delay times of repeatable ignition cases are recorded. For each test, a 0.1 g sample is loaded in a visible loading tube, which is finally injected into the furnace, using pressurized air, once the expected furnace temperature is achieved and maintained as stable. The amount of air in the furnace chamber is sufficient for stoichiometric burning of the injected biomass particles. The flue gas is discharged via an outlet placed at the top of the furnace. The calibrations of photosensitive elements, temperature, and oxygen concentrations inside the reactor are repeated after each test is completed.

2.2. Ignition Temperature Estimations. Thermogravimetry (TG) and differential thermogravimetry (DTG) curves often have been employed to identify the ignition temperature and burnout temperature, which provides fundamentals of the fuel properties for analyses of the ignition phenomena discovered in the down-fire reactor. The characteristic temperatures obtained from the different methods are slightly different, but the values can be compared quantitatively as long as a consistent definition of these quantities is used. By analyzing TG and DTG curves, the ignition temperatures (T_i) of solid fuels are often identified as (1) the temperature at which the combustion rate rises to 1 wt % min^{-1} at the start of a major combustion process;[12] (2) the onset temperature of devolatilization and the maximum reactivity temperature (DTG_{max});[13] and also (3) the temperature at which the weight loss curves in the oxidation and pyrolysis experiments diverge.[12] Because of concerns about the reliability of methods based on individual TGA run,[14] in this work, the TG and DTG tests of all of the studied fuel samples will be conducted and compared under inert (without oxygen presence) and oxidative (with oxygen presence) conditions, at various particle sizes.

2.3. Single Particle Model (SPM). Combustion performance of biomass in a high-temperature furnace has been comprehensively investigated using a single particle model in our previous work,[15] by considering particle heating, drying, devolatilization, volatile combustion, and char oxidation. Once exposed in the furnace at high temperatures, the biomass particle is heated by the surrounding furnace wall and oxidizing agent via the radiation and convection approaches, respectively. The temperature gradient is also considered, and the intraparticle heat transfer is governed by the conduction. The drying and devolatilization start when the local temperature inside the particle reaches the respective reaction temperatures, which may occur simultaneously until the biomass particle is completely dried. The released amount of volatile, the release rate, and the volatile species are highly dependent on the fuel type and heating conditions (e.g., final temperature and heating rates), which theoretically affect the ignition behavior of biomass. Therefore, the ignition behavior of biomass could be predicted with the assistance of understanding the devolatilization performance.

In the model, it is assumed that the biomass particles are spherical due to the fine particles at sizes in the range of 60−800 μm. In addition, the drying process is assumed to be independent of the combustion process. The mass and energy equations presented below describe the evolution of volatile components:

$$\frac{m_v(t)}{m_{p,0}} = \int_0^t (\alpha_1 k_1 + \alpha_2 k_2) \exp\left(-\int_0^t (k_1 + k_2)\, dt\right) dt \quad (1)$$

$$\frac{\partial T_p}{\partial t}(\rho_M C_{P(M)} + \rho_{DB} C_{P(DB)} + \rho_{Char} C_{P(Char)} + \rho_{Ash} C_{P(Ash)}) = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 k' \frac{\partial T_p}{\partial r}\right) + \tilde{Q} \quad (2)$$

The two-competing model is employed to simulate the devolatilization process and predict the high temperature volatile yield. To accurately predict the effects of particles size on the devolatilization process, the particle size changes of biomass during the thermal conversions are comprehensively considered. More-detailed descriptions about the model are available in our previous work.[15] Finally, comprehensively considering the subprocesses of particle heating, drying, and devolatilization, this model will be employed to predict the time scales of devolatilization at varying degrees to help in better understanding the ignition behavior.

3. RESULTS AND DISCUSSIONS

3.1. Combustion Characteristics of Biomass Materials in Thermogravimetric Analysis (TGA). TGA is a very useful method to study fuel properties from a fundamental point of view, which provides supportive information for analyzing the ignition behavior of solid fuels.[16] Three biomass materials are studied in this work, including straw, softwood, and torrefied softwood; all of the biomass materials are milled and then selected as samples for testing. The TG and DTG curves of the three studied biomass materials under the air conditions are shown in Figure 2. Generally, the first peak of the combustion is attributed to the devolatilization of hemicellulose and cellulose, which are more-reactive chemical compounds of biomass than lignin.[17] It is obvious that the straw has a higher

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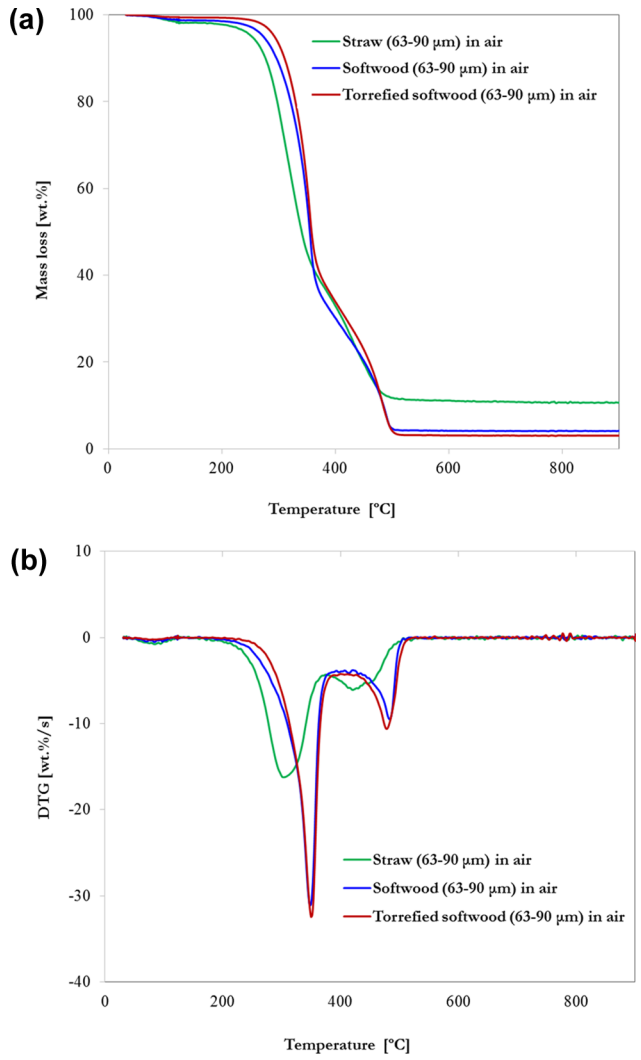

Figure 2. Combustion characteristics of three biomass materials in thermogravimetric analysis (TGA): (a) thermogravimetry (TG) curves and (b) differential thermogravimetry (DTG) curves.

reactivity than the softwood; thus, with an increase of temperature, the decomposition of straw biomass starts early and the first peak in the DTG curve is located at 313 °C, while the softwood requires a higher temperature to initiate its thermal conversions, and, hence, its first peak in the DTG curve is observed at 352 °C.

Torrefaction has been employed to improve the biomass fuel quality by releasing its hemicellulose and part of its cellulose, alternating biomass fuel properties with enhanced energy density and reduced reactivity in order to be similar, in terms of quality, to coal. In this study, the torrefied biomass is produced by exposing the softwood particles in the oxygen-free oven for 30 min at 250 °C. In the TG curves, a delayed decomposition of the torrefied softwood is observed, especially at the initial stage of devolatilization, indicating that the hemicellulose was released during torrefaction while the devolatilization is relative to the cellulose, which has a lower reactivity than hemicellulose. In addition, the first peaks of softwood and torrefied softwood are overlapped at 352 °C, which was attribute to the decomposition of the cellulose, which is the major component of softwood. Therefore, the nature of biomass fuel combustion does not change significantly by torrefaction.

3.2. Thermal Characteristics of Softwood under Air and N_2 Conditions in Thermogravimetric Analysis (TGA).

The thermal characteristics of softwood under air and N_2 conditions are investigated in TGA; the results are shown in Figure 3. There is a common approach to identify the ignition

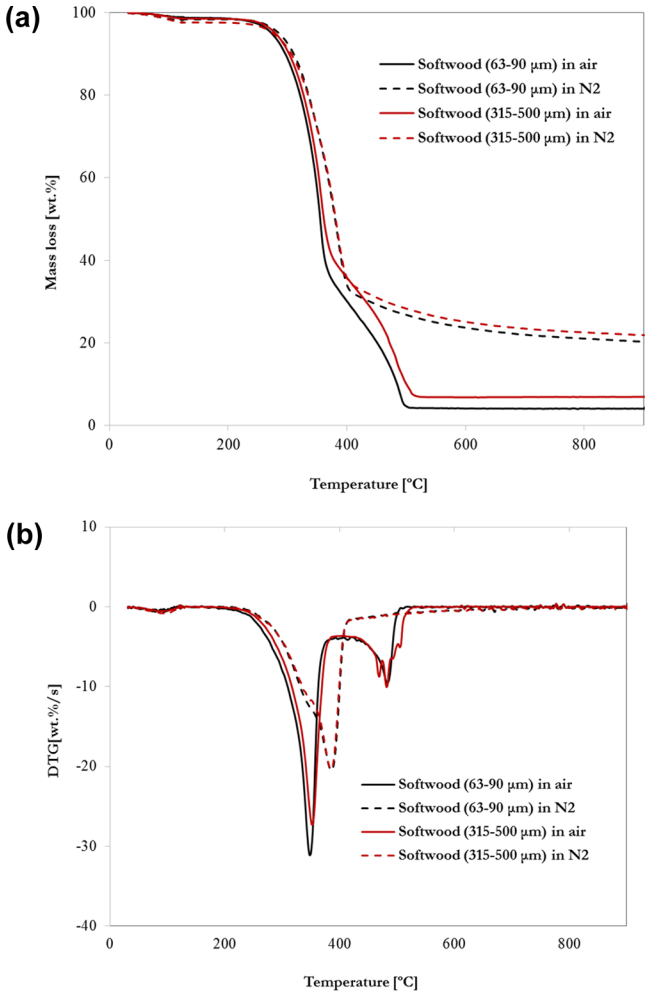

Figure 3. Thermal characteristics of softwood under air and N_2 conditions in TGA: (a) TG curves and (b) DTG curves.

temperature at which the deviation of mass losses in inert and oxidizing atmospheres is observed.[16] From the comparison of the pyrolysis and combustion profiles of softwood, the ignition mechanism can be estimated. The TG curves showed slight differences between the mass losses under oxygen-free and air conditions in a temperature range up to ca. 400 °C. A similar amount of volatiles is released under air conditions as in the case observed under oxygen-free conditions, indicating that the release of volatiles is primarily driven by the increase in temperature, rather than the presence of oxygen. The slight differences may be attributed to the higher thermal conductivity of air than that of nitrogen (49.4 and 48.7 mW/(m/K), respectively, at 1 MPa and 400 °C).[18,19] At temperatures above 400 °C, the mass loss in nitrogen changes slightly, because of the slow process of devolatilization, whereas, in air, it was observed a sharp decrease in mass loss, because of oxidation of the remaining char. In the oxygen-free case, the total mass remaining is converging to the sum of fixed carbon and the

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inherent ash, whereas, in an air atmosphere, it is similar to the amount of inherent ash.

The comparison of behavior of fuels in an inert and an oxidative atmosphere indicates the mechanism of ignition. For two investigated samples, at temperatures below 400 °C, the mass loss occurs in the same way, both in oxygen-free and air atmospheres; thus, according to Arenillas et al.,[16] the ignition is recognized as homogeneous. As described by Arenillas et al., the observed mechanism may be attributed to the composition of volatile compounds, which are more stable than in the heterogeneous ignition case; therefore, they are evolved at relatively high temperatures, where the char can react and, thus, the entire particle burns together.

Moreover, the impacts of particle sizes on the thermal conversion processes of softwood in TGA have also been investigated. In the tests, a slight difference was noticed when conducting the pyrolysis and combustion process in TGA for varying sizes of softwood samples. Figure 3 lists the TG and DTG curves of two groups of softwood particles: 63−90 μm and 315−500 μm. It is obvious that the corresponding temperatures of the first peaks of either the combustion process or the pyrolysis process are not affected when increasing the particle sizes, and, consequently, the TGA results have failed to discover the impacts of particle size on the thermal conversion behavior of biomass. However, it can be seen that the presence of oxygen can accelerate the devolatilization process and, thus, potentially has an impact on ignition behavior. The higher peak of devolatilization of small softwood particles than that of large softwood particles shows that the large biomass particle has a lower reactivity, while the peaks of char oxidation are almost the same for large particles.

3.3. Effect of Biomass Type on the Ignition Delay Time. As discussed in section 3.2, the TGA results have failed to identify the effects of particle size on the thermal behavior, which could be attributed to the low heating rates and the stationary of biomass particles. An advanced ignition testing approach is thus required to understand the ignition behavior of different biomasses and the impacts of particle sizes. As mentioned previously, ignition temperature is not a fundamental parameter of the fuel, which are affected by the particle size, heating rate of the particle, and the surrounding atmosphere.[4] When a biomass particle enters a pulverized fuel flame, it is rapidly heated to a final temperature that is far above its ignition temperature. Therefore, the ignition delay times at varying temperatures will be of interest in this work, which becomes a key factor that can be referenced for biomass boiler design and retrofitting, and also for optimization of the biomass combustion or co-firing performance, by incorporating the transport phenomena and the surrounding atmosphere.

Figure 4 presents the impacts of fuel types on the ignition delay time of biomass. Note that this figure only shows the cases with ignition occurred, while the tests without detectable or repeatable ignitions are excluded. Generally, the ignition delay times of all of the biomass materials decrease as the furnace temperature increases. In addition, it is observed that, being injected into the furnace, softwood particles take more time to ignite than the straw particles and this can be explained as the high reactivity of straw biomass that promotes its ignition process. Specifically, the straw particles at sizes of 63−90 μm were successfully ignited at temperatures slightly over 500 °C and the corresponding ignition delay time is 0.535 s at 508 °C.

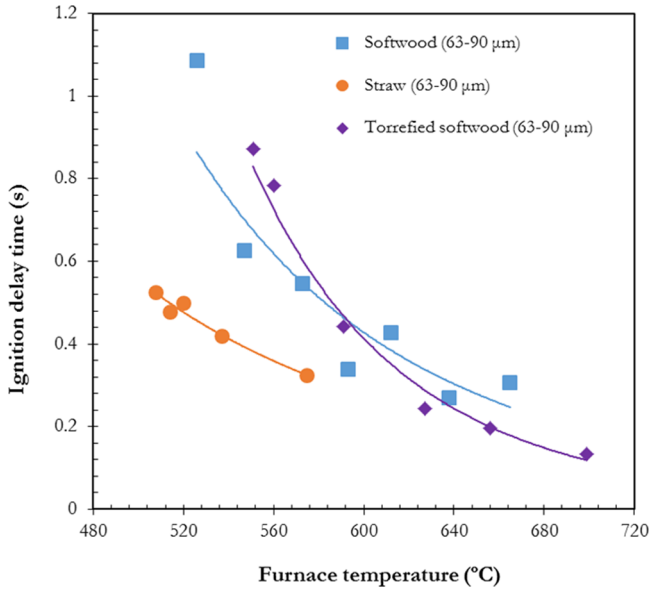

Figure 4. Effect of fuel type on the biomass ignition behavior.

The ignition delay times of softwood ranged from 0.269 s at 665 °C to 1.085 s at 526 °C; the tests performed at furnace temperatures under 520 °C failed to detect an ignition. Ignitions of torrefied biomass also were conducted; however, the curves of its ignition delay times cross that of the raw softwood. According to their reactivity, the ignition delay time of the torrefied biomass is expected to be longer than that of untreated biomass at the same temperature; thus, the ignition behavior of the raw and torrefied softwood are reasonable at temperatures under 590 °C. Whereas at relative high temperatures, torrefied biomass shows a shorter minimum ignition delay time than that of raw biomass, which could involve the change of mechanisms from homogeneous ignition to heterogeneous ignition, because the high porosity after torrefaction improves its char oxidation process and thus the ignition occurs at the particle surface. Further studies on the effects of torrefaction on the biomass ignition mechanism are required.

3.4. Effect of Particle Size on the Ignition Delay Time. Figure 5a presents the impact of particle size on the ignition delay time of biomass at varying temperatures. Larger particles clearly require high temperature to ignite, and the converging minimum ignition temperatures are increased when increasing the size of the biomass particles; this could be explained as the low reactivity of the large biomass particle, as discussed in the TGA results. The ignition of the largest-size particles (630−800 μm) were unable to be detected by photosensitive elements at furnace temperatures below 700 °C. In addition, at the same furnace temperature, a longer residence time is needed to ignite the larger biomass particles. For example, 0.269 s will be needed to ignite the 63−90 μm softwood particles at 638 °C, while 0.537 s is required to ignite the 315−500 μm softwood particles at the same temperature.

Figure 5b shows the ignition delay times of the three biomass materials with varying sizes at a particular selected temperature (650 °C). From these results, it can be concluded that the ignition of biomass is delayed as its size increases, while, conversely, to achieve a short ignition delay time for the same biomass material, an efficient approach is to reduce its particle size. These results will help to understand and control the

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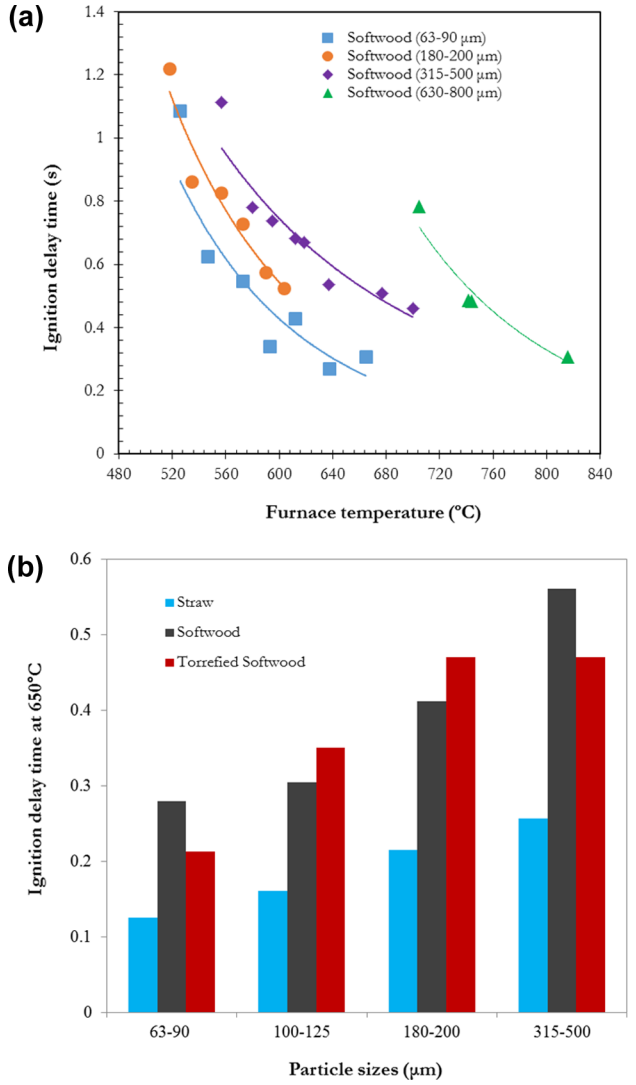

Figure 5. Effect of particle sizes on the biomass ignition behavior: (a) softwood at varying temperatures and (b) various biomass materials at 650 °C.

processes of pulverized biomass combustion or co-firing with coal in coal-fired boilers; therefore, the biomass particle size can be optimized if the fuel properties and co-firing boiler configurations are known. The results can also be utilized to realize a promising biomass combustion performance by adjusting the size of biomass particles to match that of coal, with the objective of observing large percentage biomass co-firing in the exits of pulverized coal boilers.

3.5. Discussions of Ignition and Devolatilization. Biomass particles, when entering the furnace chamber, are rapidly heated to the furnace temperature, during which its thermal conversion process becomes very complicated, because of the heating of the particle by its surrounding environment, as well as the processes of drying, devolatilization, and char oxidation. It is still debatable whether coal ignites homogeneously or heterogeneously,[3] because of the challenge of identifying it using experimental approaches. However, Zhang and Wall reported that the high volatiles content in coal leads to a homogeneous ignition.[2] Compared to coal, biomass contains high amount of volatiles, for example, the volatiles content in the studied softwood is over 80% on a dry basis; therefore, one can reasonably assume that the biomass ignition in this study is dominated by the homogeneous ignition mechanism. In addition, according to the TGA results (see section 3.2), the ignition of softwood is identified as a homogeneous mechanism, which, therefore, does not begin until volatiles are released. It is known that the released amount and release rate of volatiles are determined by the fuel types and parameters involves in the heating process, such as the furnace temperature and heating rate. Therefore, it is interesting to discover the relationship between the biomass ignition and its devolatilization process.

The ignition delay times of softwood at 63−90 μm have been determined at varying furnace temperatures in the down-fire furnace; they are plotted in Figure 6. An obvious trend is

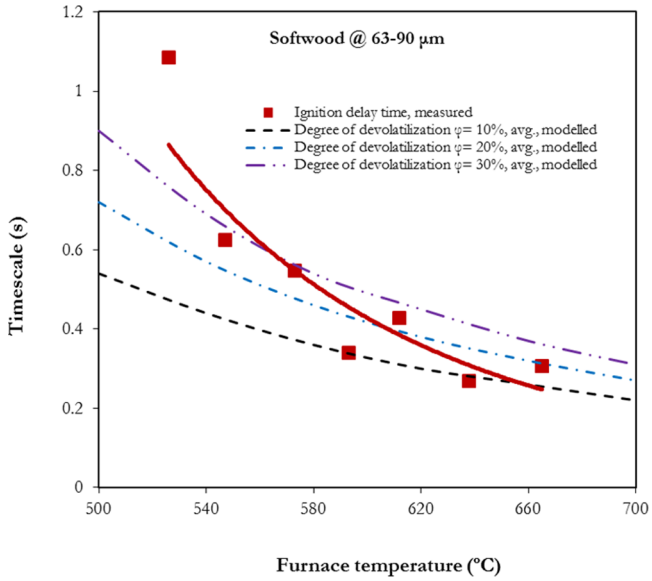

Figure 6. Volatile release times versus ignition delay times.

noticed, that the ignition time decreases as the furnace temperatures increase. On the other hand, the released amount of volatiles increases as the furnace temperature increases, while the residence time determines the released amount of volatiles at certain temperatures: a shorter residence time corresponds to a smaller amount of released volatiles. The degree of devolatilization can be mathematically identified and defined as described below:

$$\varphi_{devo} = 1 - \frac{f_v}{f_{v,0}}$$

where f_v is the volatile content in the solid residuals and $f_{v,0}$ is the initial volatile content in the raw biomass, based on the standard proximate analysis.

Therefore, it is interesting to understand the relationship between the ignition behavior of biomass and the devolatilization process. The numerical combustion model of single biomass particles was developed in our previous work,[15] which is able to predict the time scales of varying degrees of devolatilization. Note that the prediction of devolatilization time in the model is affected by the external and internal heating processes of the particles.

Figure 6 compares the time scales of ignition delay time, and the time scales of devolatilization at various degrees of devolatilization (10%, 20%, and 30%). It shows that biomass at low furnace temperature requires the ignition of more

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volatiles released, and the impacts are very sensitive to the devolatilization process that is determined by the furnace temperature. The optimized ignition delay time is as quick as 0.26 s with 10% degree of devolatilization at the furnace temperature of 660 °C. It can be predicted that, at a sufficiently high furnace temperature, biomass could ignite before the start of devolatilization, indicating that a heterogeneous ignition has occurred at the particle surface. Therefore, the ignition mechanism of biomass could be switched from homogeneous ignition to heterogeneous ignition. Obviously, the furnace temperature needed to alternate the ignition mechanism will be dependent on the fuel type and particle size. This conclusion can be used to control and optimize the biomass combustion or co-firing performance, based on the ignition behaviors, by modifying the particle sizes and the local temperature in the near-burner zone.

4. CONCLUSIONS

This paper has investigated the ignition behavior of biomass particles for optimization of co-firing performance. Three types of biomass materials were studied, including straw biomass, softwood, and torrefied softwood. Prior to the experimental investigations, thermogravimetric analysis (TGA) of biomass fuels has been performed to understand their fuel properties. Finally, the ignition behavior studies of biomass particles were conducted in a down-fire reactor.

The TGA results in this work have failed to identify the impact of particle size on the ignition behavior of biomass using TGA, although such research has been attempted previously, which is primarily limited by its low heating rate and stillness of particles. However, it has been observed that, at the same furnace temperature, larger biomass particles require more time for ignition to start than a smaller particle, according to the testing results in a down-fire reactor. A TGA approach has been used to determine the ignition temperature by identifying the diverse point of thermogravimetry (TG) curves of biomass with and without the presence of oxygen. In this work, an acceleration of the devolatilization rate of softwood is observed by presenting the oxygen, but its TG curve almost overlaps with that of the pyrolysis case; accordingly, it is concluded that softwood is ignited homogeneously. Furthermore, the ignition delay times of all of the biomass materials decrease as the furnace temperature increases. In addition, it is observed that, after being injected into the furnace, softwood particles require a longer residence time to be ignited than straw particles, which agrees well with their reactivity analysis in TGA. While the ignition delay time curve of torrefied softwood crosses that of softwood, it could be explained as a change of mechanisms from homogeneous ignition to heterogeneous ignition; further studies on this ignition mechanism are required. In addition, at a sufficiently high furnace temperature, the ignition of biomass will start directly at the particle surface without requiring devolatilization to occur; therefore, it is concluded that the ignition mechanism of biomass is highly dependent on the furnace temperature and the degree of devolatilization. Generally, the ignition behavior and consequent combustion performance of biomass can be modified by adjusting its degree of devolatilization, as well as by controlling the biomass particle size and the surrounding gas temperature; ultimately, the processes of pulverized biomass combustion or co-firing with coal in coal-fired boilers can be optimized.

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Notes

The authors declare no competing financial interest.

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NOMENCLATURE

Symbols

f = content in the solid residuals
k = reaction rate constant expressed in Arrhenius form (kg/(m^2 Pa s))
k' = thermal conductivity (W/(m K))
m = mass (g)
$\tilde{Q}$ = reaction heat absorbed by solid remains (J)
r = particle radius (m)
R = gas universal constant; R = 8.3143 J/(mol K)
T = temperature (K)
α = volatile yield factor

Subscripts

DB = dry biomass
devo = devolatilization
M = moisture
p = particle
v = volatile
0 = initial value
1 = refers low temperatures
2 = refers high temperatures

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